Title: Analysis of the Rhodotron Pulsed Beam Impact on the Northstar Mo100 Target Window

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Analysis of the Rhodotron Pulsed Beam Impact on the Northstar Mo100 Target Window

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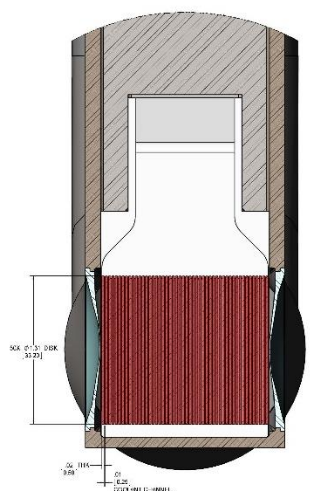
Introduction

Northstar has elected to use rhodotrons rather than linear accelerators to deliver the electron beam to their targets. This decision has imposed a much lower frequency beam pulse on the target, resulting in short duration high power deposition. The impact on the target window is of particular importance.

The target is a stack of Mo100 disks 0.5 mm thick and 29 mm in diameter, separated by 0.25 mm coolant gaps. There is a beam entry window on each side of the stack. There are 2 rhodotrons per target, each delivering nominally 120 kW to each side of the target. The target and target housing with windows are shown in Figure 1.



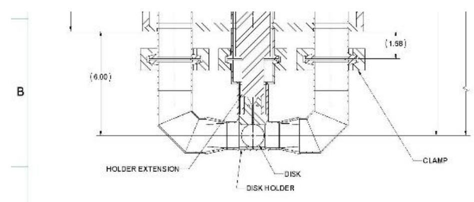


Figure 1. Target and target holder, with windows. In the view on the left, 2 beams will strike the target from each end, in the plane of the page. In the view on the right, the target is bottom center, the beam is into the page.

Steady State Analysis

The steady state analysis of the target is reported elsewhere, but some summary is presented here for reference and completeness. The important performance parameters relevant to this pulsed beam analysis are the temperature of the window and the stress state at the operating pressure of 2068 kPa (300 psi). The beam heating profile is shown in Figure 2. The resulting target and window temperature are shown in Figure 3, with a peak window temperature near the center of 408°C.

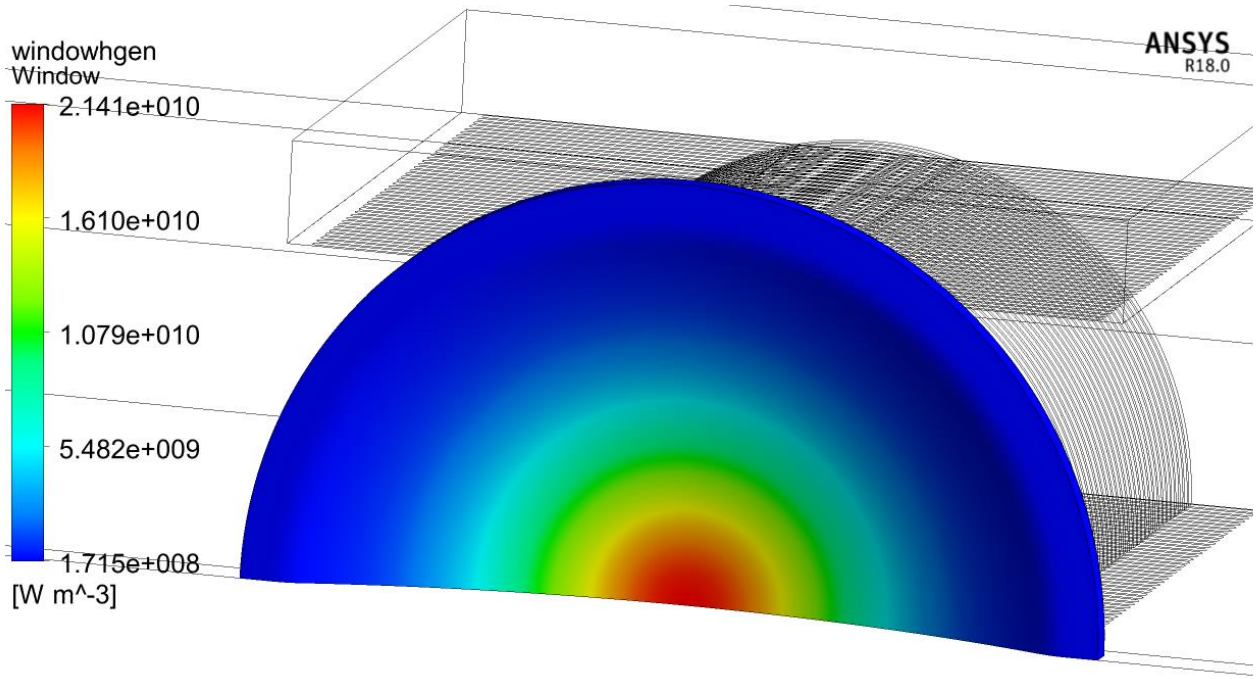


Figure 2. Window heat deposition.

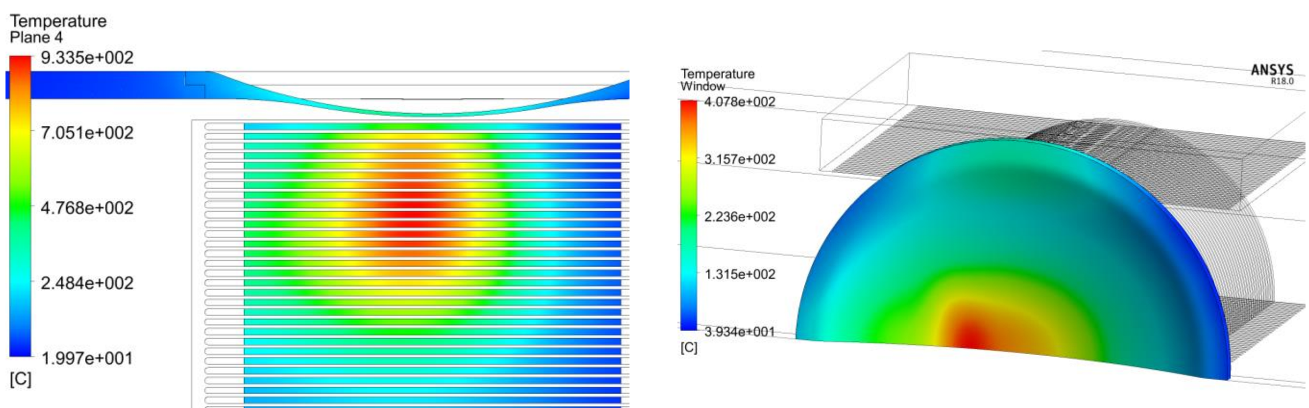


Figure 3.

The window is subjected to a primary mechanical stress (membrane plus bending) due to the pressure load, plus a secondary thermally induced stress. It is useful to consider these separately and in combination. The primary and primary plus secondary stresses are shown in Figure 4. The maximum primary stress is 258 MPa, peak combined primary plus secondary is 452 MPa.

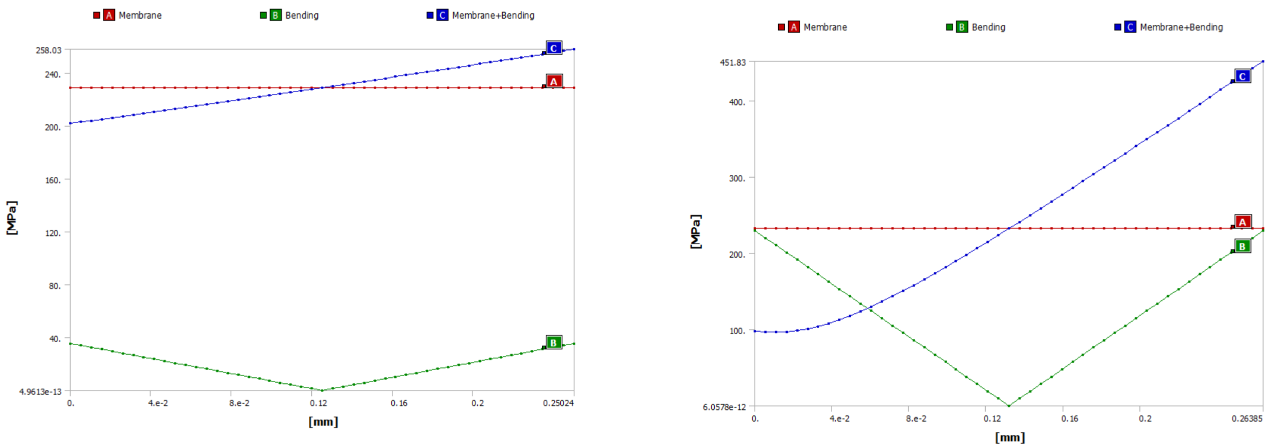


Figure 4.

Pulsed Beam Transient Analysis

The pulsed beam currently measured at IBA is shown in Figure 5. The pulse is at 25 Hz with a 5 ms pulse width. The transient temperature response is shown in Figure 6. There is a nominally 200°C temperature oscillation with each pulse.

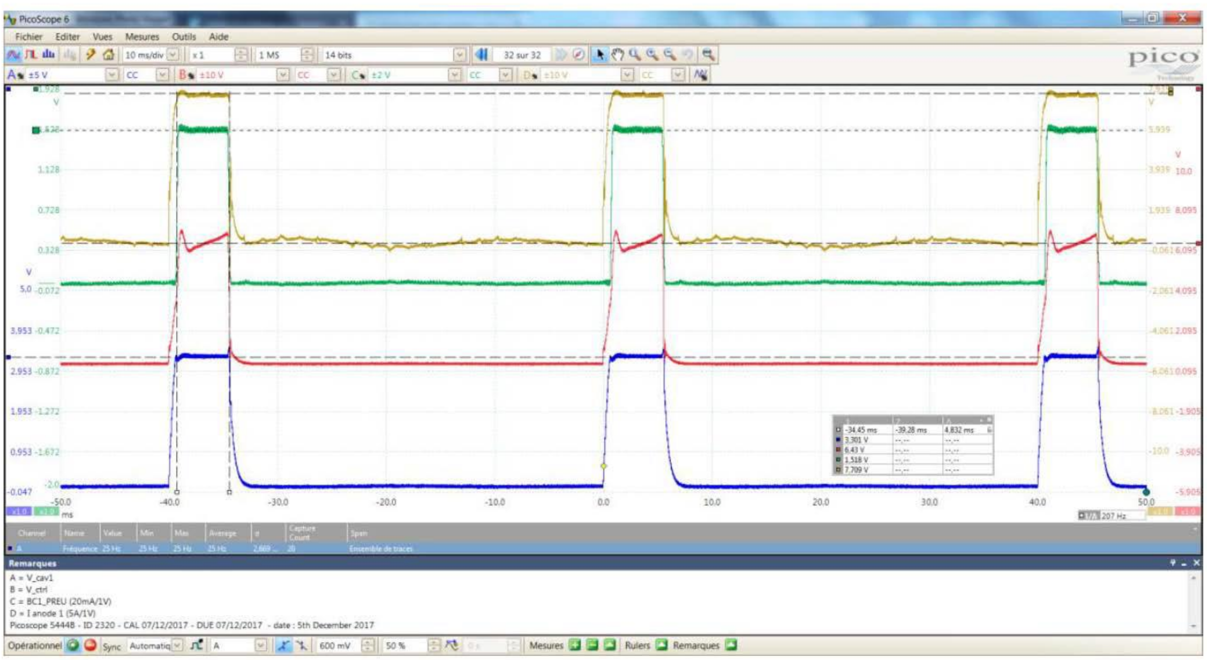


Figure 5. Pulsed beam structure, as of May 2018. Blue is voltage, green is current. The pulse is 5 ms at 25 Hz, of 12.5% duty factor.

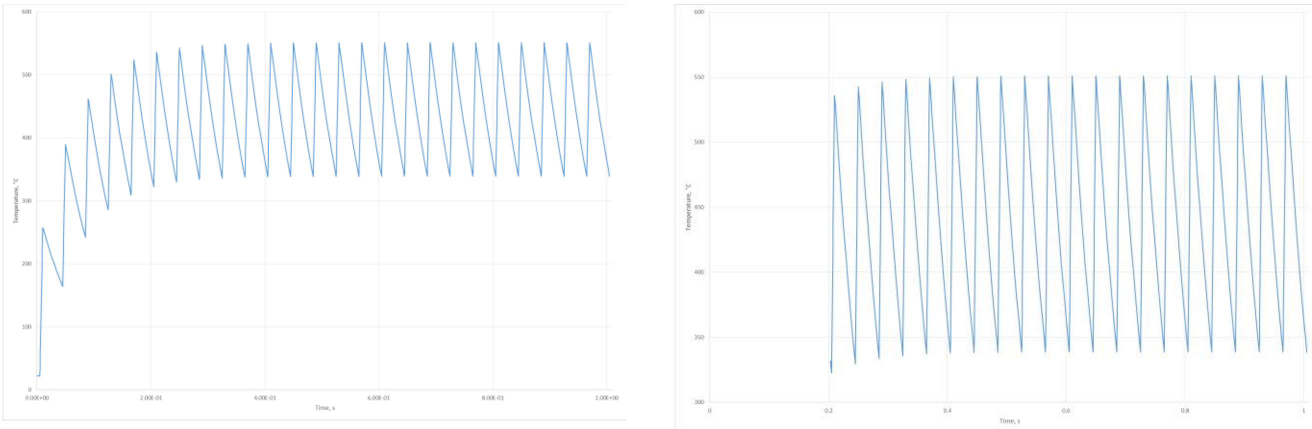


Figure 6. Pulsed beam temperature response.

Fatigue

At 25 Hz and operating 6.5 days per week, 52 weeks per year, the window will be subjected to $1.75X10^9$ cycles. Fatigue curves for a given material at a given temperature are generally expressed as number of cycles to failure vs equivalent stress. In our case, the equivalent stress is 452 MPa at 550°C, the peak temperature during the pulse. This is a conservative measure of equivalent stress because of the large secondary stress contributor. However, it is the thermal stress that is cycling, the mechanical primary stress is a static applied stress invariant with time. There are no available similar load cases found in the literature.

Specialty Metals is the supplier for the Inconel 718 used in the window. In their material data sheet (http://www.specialmetals.com/assets/smc/documents/inconel_alloy_718.pdf), on pp 17, they list fatigue strength at 10^8 cycles and 1000°F (537°C) as 90 ksi (620 MPa). As fatigue curves tend to approach an isotope, as will be seen below, and since 620 MPa is much greater than the window equivalent stress, no failure due to the pulsed beam can be expected based on this referenced data.

Kyle Buchholz, U. of Florida, did a study "High-Cycles Fatigue of Inconel 718" (https://nationalmaglab.org/images/education/searchable_docs/college_early_career/reu/2017/buchholz.pdf). The plot of that data, along with data from 3 other sources, is shown in Figure 7. This shows approaching a minimum of 500 MPa or greater at about $2X10^6$ cycles. This is also encouraging data in support of window life beyond one year.

Another fatigue curve from "Atlas of Fatigue Curves," American Society for Materials, H. E. Boyer, 1986, is shown in Figure 8. In this data, the fatigue life has reached an asymptote at 10^8 cycles corresponding to 538°C and 420 MPa. This is much lower than the Specialty Metals data, and roughly equivalent to the Northstar window condition.

Strain range is another parameter besides equivalent stress for evaluation fatigue life. Calculated strain for the Northstar window at the maximum and minimum temperatures during the pulse are shown in Figure 9. Strain range, in percent, is 17. Figure 10 shows fatigue life as a function of strain range (AFCI Material Handbook, Rev. 5, LA-CP-06-0904). By this curve and this criteria, the target is likely to fail on very early. It should be noted that it is generally accepted that thermal fatigue is strain controlled, whereas mechanical fatigue is stress controlled ("Thermal Fatigue of Metals," A Weronski and T.

Hejwowski, Marcel Dekker, Inc, 1991). Having said that, the source of Figure 9 states “The investigators observed no apparent strain rate effects in the elastic regime.” The target window is well within the elastic regime. Hence, while the possibility of early failure due to strain range should not be discounted completely, it is not likely to cause failure. Further, the expected operating frequency will be 50 Hz with the same duty cycle. The temperature oscillations will be closer to 100°C, with strain range similarly reduced.

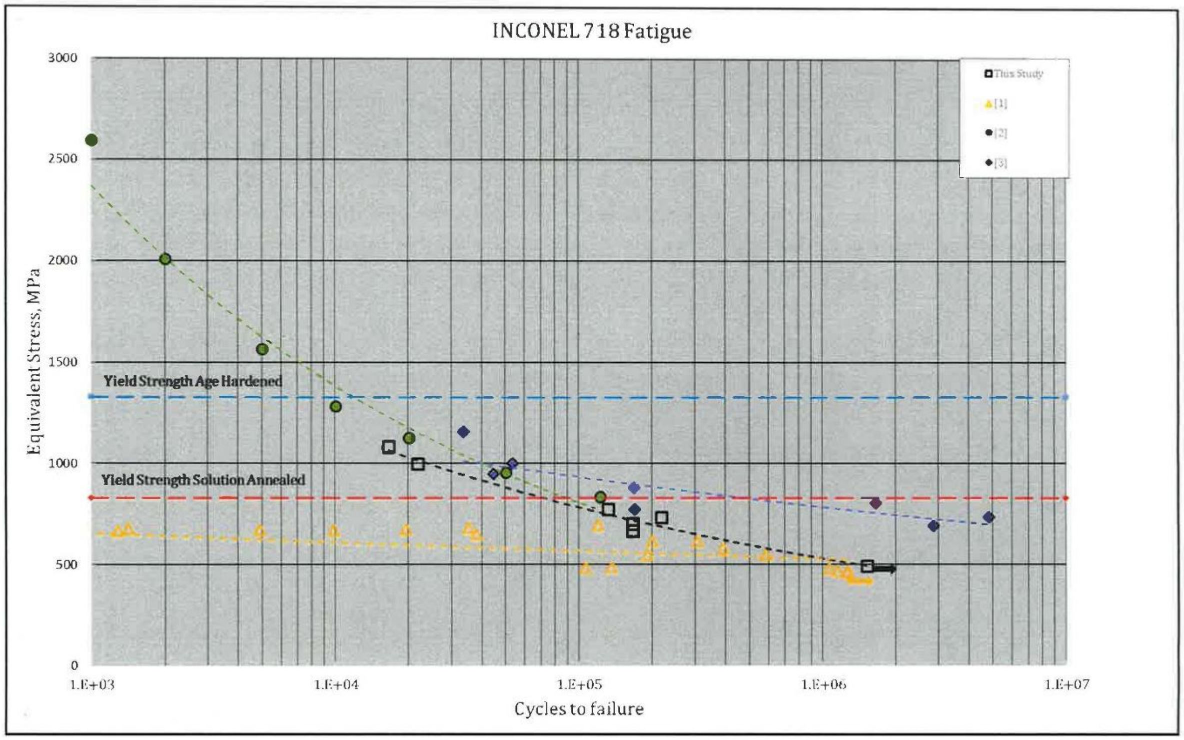


Figure 7.Inconel fatigue data from K. Buchholz, reference above.

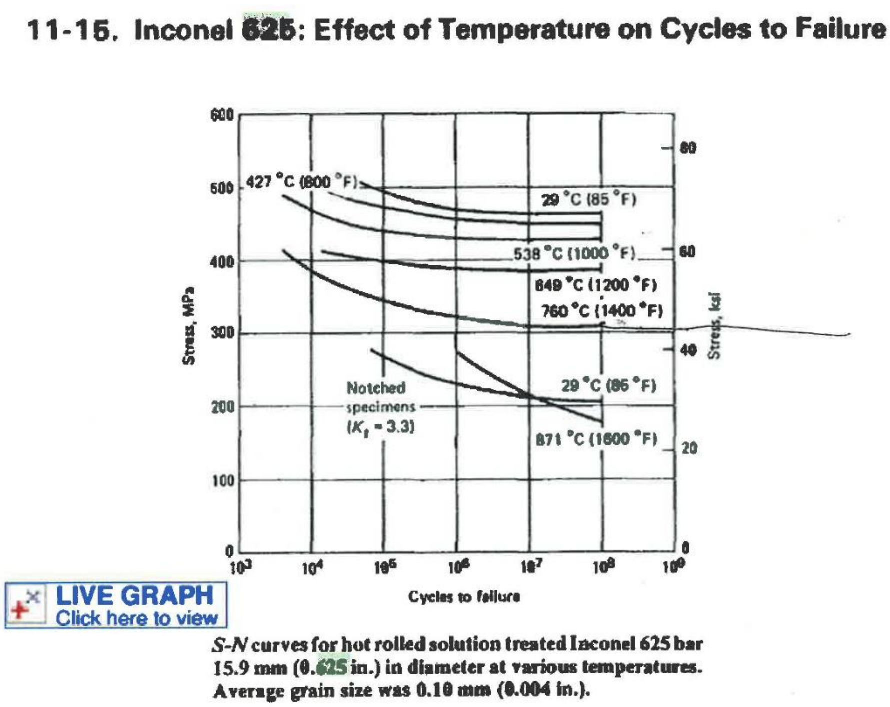


Figure 8. Fatigue curve for Inconel 718 from “Atlas of Fatigue Curves.” In this curve, the fatigue life at 538 C is about 420 MPa.

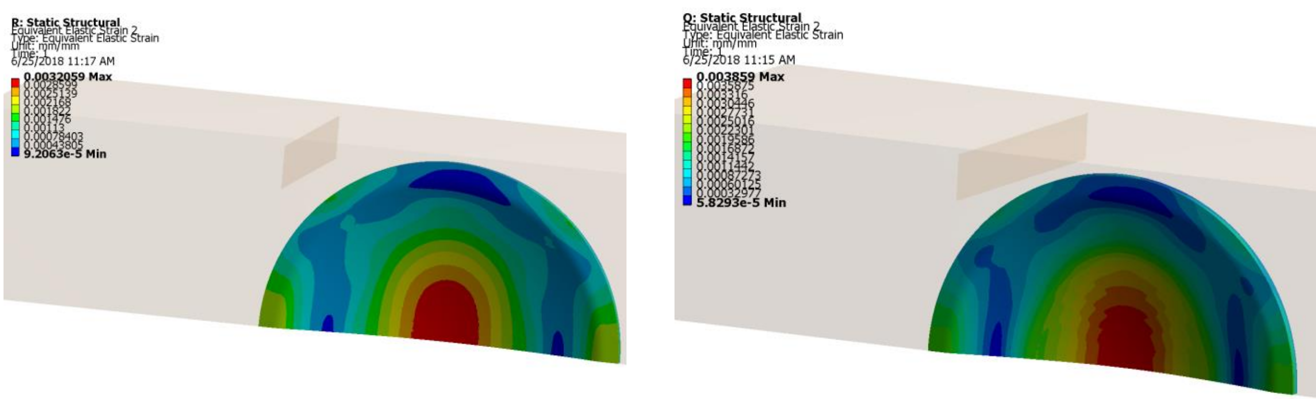


Figure 9. Northstar window strain at the extremes of the pulsed heating. Strain at target center is .0032 at 338°C (left) and .0039 at 550°C (left).

Materials Data for Particle Accelerator Applica
Chapter 2. Design Properties of Alloy 718

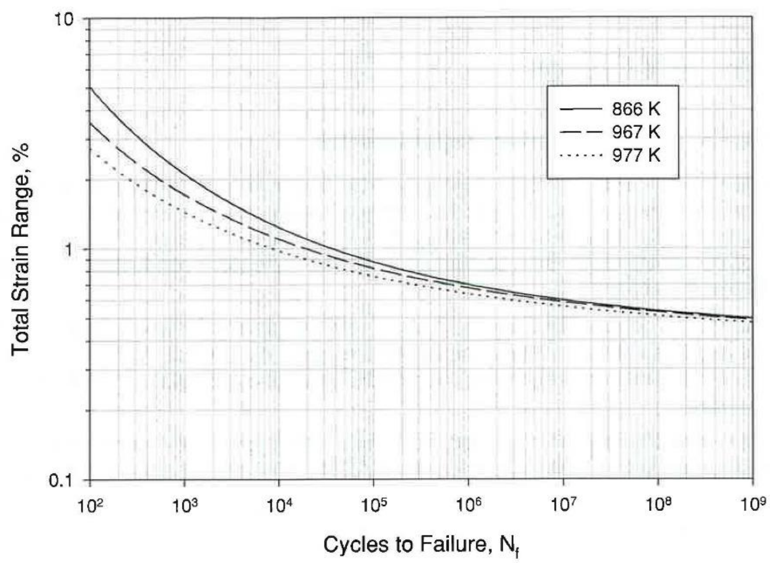


Figure 2-40. S-N curves for fatigue of Alloy 718 for temperatures of 866 K, 922 K, and 977 K.

Figure 10. Fatigue life of Inconel 718 based on strain range.

Conclusion

The most important conclusion is that the fatigue life of the Northstar window, with its time invariant mechanical load and a superimposed cyclic thermal load, has no close parallel in the literature. Also, the equivalent stress curves referenced herein are not mutually consistent. There are too many variables in material condition for a direct comparison with published data. Further, while the target stress is well within the elastic regime, the strain range is high, so that criteria for fatigue life cannot be completely discounted. So, while available data suggests that the window can survive 10^9 cycles (1 year), the possibility of premature failure cannot be ignored. An experimental replication of the pulse strength and duration is highly recommended.

A pulse frequency increase from 25 to 50 Hz is expected. This significantly reduces the thermal oscillations and strain range concerns but uncertainty is predicting fatigue life remains.